



Adapting aviation to a changing climate: Key priorities for action

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ABSTRACT

The need for the global aviation sector to adapt and develop resilience to the potential impacts of climate change is gaining momentum. This paper expands on previous analysis by EUROCONTROL to further clarify the expected impacts for the sector. It identifies key questions to ask when considering a climate risk assessment, looks at developing a climate adaptation plan and identifies potential resilience measures. Finally, the paper presents the outcomes of a recent workshop on Adapting Aviation to a Changing Climate identifying four key priorities for action to develop climate change resilience. It concludes that identifying knowledge gaps, raising awareness and promoting collaboration are key steps in building climate change resilience for the aviation sector at both European and global level.

1. Introduction

The need for the global aviation sector to adapt and develop resilience to the potential impacts of climate change is gaining momentum. Risks can be both operational and financial and include disruption to operations and damage to infrastructure as well as changes to baseline conditions and infrastructure requirements. This paper expands on previous analysis, presented by EUROCONTROL at the Air Transport Research Society World Conference, 2014, to further clarify what the expected impacts for the aviation sector might be and how they can be addressed. In particular it highlights the need for action in areas which are expected to experience both high growth in demand and significant climate change impacts.

Following this, the paper considers the need for organisations to carry out a risk assessment to assess their potential vulnerability to climate change. It identifies key questions to ask when considering a risk assessment and highlights the methodologies which are available. It then looks at identifying a climate adaptation strategy and plan and identifies potential resilience measures to address key impacts.

Finally, the paper presents the outcomes of a recent workshop on Adapting Aviation to a Changing Climate which identified four key priorities for action to develop climate change resilience. It concludes that identifying knowledge gaps, raising awareness and promoting collaboration are key steps in building climate change resilience for the aviation sector at both European and global level.

2. Defining resilience

Adaptation, and resilience are terms which can be interpreted and

applied in various ways according to the specific context (Levina and Tirpak, 2006). Although they are often used interchangeably, there is a distinct difference between the two. For the purposes of this paper the definitions from the IPCC Fifth Assessment Report (IPCC, 2014) will be used, namely:

Adaptation: “The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effect” (IPCC, 2014 p.118).

Resilience: “The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation” (IPCC, 2014 p.127).

Putting this in a more aviation-specific context, climate adaptation means adjusting, changing or improving operations, infrastructure and processes so as to be prepared for expected climate changes, and climate resilience means developing the ability for operations and infrastructure to be able to withstand and recover from external perturbation.













3. Climate risks for aviation

Burbidge (2014) gave an overview of the key risks that European aviation can expect from climate change as well as an analysis of how these risks will affect different stakeholders. This section will give a brief recap of those risks before discussing some additional potential impacts which may affect Europe and other areas of the world, namely

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Table 1
Climate impacts for European aviation by stakeholder (drawn from EUROCONTROL et al., 2014).

Climate risk	Impact	Actors	Key:	
<div></div> <div>Precipitation change</div>	<ul style="list-style-type: none">• disruption to operations e.g. airfield flooding, ground subsidence• reduction in airport throughput• drainage system capacity• inundation of underground infrastructure (e.g. electrical)• inundation of ground transport access (passengers and staff)• loss of local utilities provision (e.g. power).	<div>→ AO ANSP</div> <div>→ AO ANSP</div> <div>AO</div> <div>AO</div> <div>→ AO ANSP </div> <div>→AO ANSP </div>	<div>Aircraft operators</div> <div>→</div> <div>Airport operators</div> <div>AO</div> <div>ANSP</div> <div>ANSP</div> <div>External</div> <div></div>	
<div></div> <div>Temperature change</div>	<ul style="list-style-type: none">• Changes in aircraft performance• Changes in noise impact due to changes in performance• heat damage to airport surface (runway, taxiway)• increased heating and cooling requirements• Increased pressure on local utilities e.g. water and power (for cooling).	<div>→ ANSP</div> <div>→ AO ANSP</div> <div>AO</div> <div>AO</div> <div></div>		
<div></div> <div>Sea-level rise</div>	<ul style="list-style-type: none">• loss of airport capacity• impacts on en-route capacity due to lack of ground capacity• loss of airport infrastructure• loss of ground transport access	<div>→ AO ANSP</div> <div>→ ANSP</div> <div>AO</div> <div>→ AO ANSP </div>		
<div></div> <div>Wind changes</div>	<ul style="list-style-type: none">• convective weather: disruption to operations• convective weather: route extensions• jet stream: increase in en-route turbulence• local wind patterns: disruption to operations and changes to distribution of noise impact	<div>→ AO ANSP</div> <div>→ ANSP</div> <div>→ AO</div> <div>→ AO</div>		
<div></div> <div>Extreme events*</div>	<ul style="list-style-type: none">• disruption to operations, route extensions• disruption to ground transport access• disruption to utilities supply	<div>→ AO ANSP</div> <div>→ AO </div> <div>AO </div>		

*Sudden intense and short-lived precipitation and wind events as opposed to seasonal or annual changes e.g. storm surges, hurricanes, hail storms, lightning.

desertification and changes in biodiversity. It should also be recognised that not all stakeholders will be impacted by the same risks whilst, conversely the same risk can impact different stakeholders in diverse ways. Table 1 gives an overview of some key impacts by stakeholder, whilst Table 2 sets out how some key risks will impact stakeholders in different ways. It should also be kept in mind that impacts will be experienced at varying timescales and can be either intermittent or persistent. Impacts such as sea level rise and temperature increase will be experienced persistently but gradually, allowing for longer term planning. However, intermittent disruptive weather impacts such as heavy precipitation events or convective weather will be experienced in the shorter term and require resilience measures which can be applied proactively according to the situation.

Note that the impacts included in Table 1 are selected examples only and the significance of these risks will vary according to climate zone, geographical location and type of operations.

3.1. Changes in precipitation

For most of Europe, heavy precipitation events are likely to become more frequent (EEA, 2012). This can impact airport throughout by requiring increased separation distances between aircraft. Moreover, current aerodrome surface drainage capacity may be insufficient to deal with more frequent and intense precipitation events, leading to increased risk of runway and taxiway flooding. Underground infrastructure such as electrical equipment and ground transport access may also be at risk of inundation. And whilst snowfall is generally expected to decrease, there may be an increase in heavy snowfall days (over 10 cms), or snowfall in new areas, implying that a much greater geographical area needs to be prepared for heavy winter weather (Burbidge, 2014; EEA, 2012).

Conversely, a decrease in precipitation may lead to water restrictions which can impact both operations and infrastructure.

3.2. Increased convective weather

Forecasts as to changes to the frequency, location and intensity of storms are uncertain, although a number of studies predict that, in the longer term, the overall number of storms will decrease whilst the most powerful storms will be more intense (particularly in Northern and Western Europe) (EEA, 2012). The need to re-route to avoid large convective systems will lead to route-extensions with the attendant fuel, carbon, and time penalties (McCarthy and Budd, 2010). Particularly in summer convective weather can have an exponential effect on weather delay due to the high seasonal traffic levels. Larger, meso-scale convective systems have the potential to affect multiple hub airports in a region. This may reduce the choice of diversionary airports whilst those that are available may not have sufficient capacity for the traffic which they need to accommodate (Burbidge, 2014).

3.3. Changes in temperature

Risks for infrastructure may include heat damage to tarmac surfaces, whilst tarmac runways or aprons may experience difficulties due to surface melting during peak heat periods. There will also be a need for increased summer cooling of airport buildings with the attendant energy costs (Burbidge, 2014). Some buildings which were designed for cooler climates may not be able to maintain comfortable temperatures during very hot periods leading to overheating of equipment and health issues for staff (Thomas et al., 2009). Risks for operations include higher temperatures affecting aircraft engine thrust required and consequently impacting runway length requirements for take-offs (ICAO, in press). An increase in summer temperatures and humidity levels in some popular tourist destinations may influence tourists' destination preferences, impacting the amount, location and temporal distribution of traffic demand (EUROCONTROL, 2013b).

Table 2
Climate risks according to impact area.

Climate Impact	Impact Area		
	en-route	airport operations	airport infrastructure
Precipitation change		disruption to operations e.g. airfield flooding, ground subsidence, reduction in airport throughput	drain system capacity, inundation of underground infrastructure e.g. electrical, inundation of ground surface access
Temperature change		changes in performance / noise impact	heat damage to airport surface (runway, taxiway), increased heating and cooling requirements
Sea-level rise	impact on en-route capacity due to loss of ground capacity	loss of airport capacity	loss of airport infrastructure
Wind changes	convective weather: disruption to operations, route extensions, jet stream: increase in en- route turbulence	convective weather: disruption to operations, local wind patterns: disruption to operations, changes to distribution of noise impact	damage to infrastructure
Extreme events	disruption to operations, route extensions	disruption to operations	damage to infrastructure

3.4. Changes in wind patterns

Although there are many uncertainties regarding projections, wind directions are expected to change as the position of the jet stream and storm tracks move polewards and upwards (Thomas et al., 2009). The projected strengthening of the North-Atlantic jet stream may lead to an increase in the frequency and strength of clear-air turbulence whilst increasing westbound transatlantic flight times (Williams, 2016; Williams and Joshi, 2013). Increased deviation from the prevailing wind direction may cause runways to experience more cross-winds as the prevailing direction changes, or an airport may start to experience crosswinds but have no crosswind runway (Thomas et al., 2009). This may entail the need for a change in procedures and airspace redesign which, in turn, may incur an additional environmental risk due to the redistribution of noise impact around airports.

3.5. Sea-level rise and storm surges

Mean sea-level rise may lead to permanent inundation and capacity loss unless preventative measures, such as constructing sea defences, are taken. At some locations, ground transport links are also potentially at risk of inundation. In the longer term, the potential permanent loss of capacity at some locations could have implications for overall network capacity and operations. However, such impacts will be experienced gradually, allowing for longer term planning which can be based on cost benefit analyses.

The impacts of an increase in storm surges may be experienced in the shorter term and could result in a temporary reduction in capacity and increase in delay. However, there are likely to be significant geographical differences in impact with some areas experiencing an

increase in the number and height of storm surges and others a reduction in the frequency and magnitude (EEA, 2012).

3.6. Desertification

One key risk not identified in Burbidge (2014), and which may affect drier parts of the world including southern Europe, is desertification. Increase of existing, or emergence of new, drought regions could lead to restricted access to water supply. As well as the obvious impact of water shortages, this may cause soil erosion around the apron and runway and the potential encroachment of sand dunes on the apron. There may also be operational impacts such as sand storms disrupting operations and sand damage to airframes and engines (ICAO, in press).

3.7. Changes in biodiversity

Climate change may cause changes to both local biodiversity and wildlife migration patterns, as well as a potential increase in wildlife hazards. Biodiversity challenges will vary according to the existing local ecosystem and the way that the climate changes in the region. For example, there may be a change to the number and type of bird species around an airport. If migratory patterns change this could impact aircraft operations and increase the potential for bird strikes, particularly if there is an increase in heavy weight migratory bird populations in the area (ICAO, in press).

3.8. Growth

An additional risk to consider is growth in traffic. Despite a slight slowdown due to the economic crisis, traffic levels are still expected to

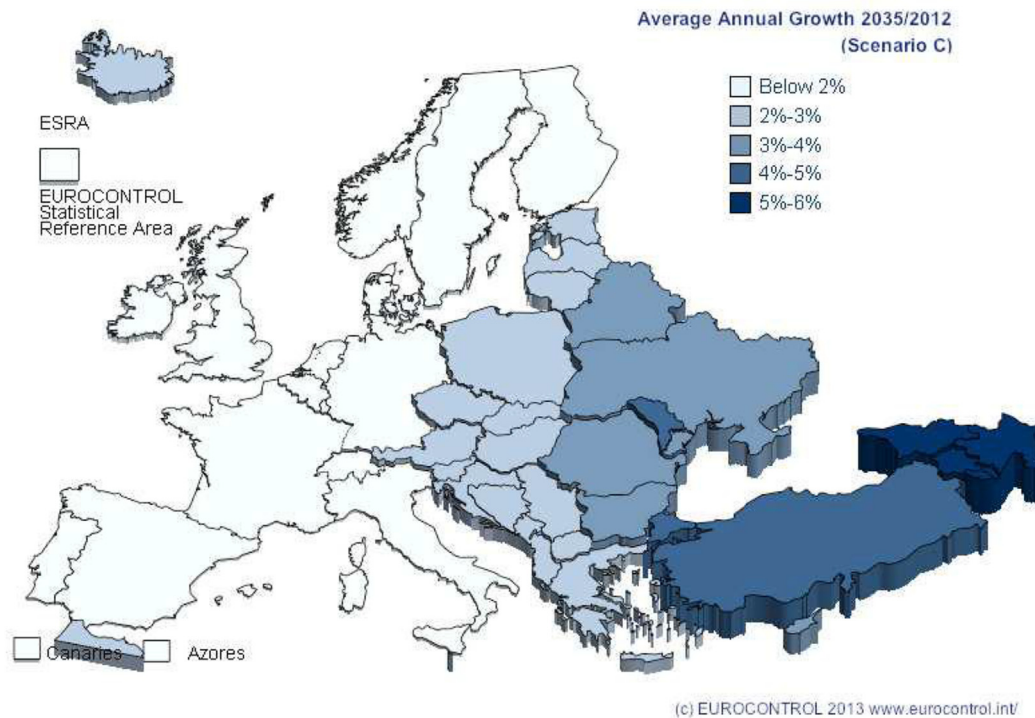


Fig. 1. Forecast annual average annual growth in European traffic 2035/2012 (Source EUROCONTROL, 2013a).

be 50% higher in 2035 than they were in 2012 (EUROCONTROL, 2013a). However, it should be noted that this growth in demand is not expected to be evenly distributed across European States and there are some particular areas of high growth in Southern and central Europe, although admittedly from a lower base (Fig. 1).

In turn this has implications for climate resilience. Between now and 2050 we can confidently expect temperatures to increase across Europe, although some areas will see larger increases than others and greater daily extremes. With precipitation, Northern Europe is expected to see an increase, particularly in the number of heavy precipitation days, whilst Southern Europe is expected to see a decrease (Morse et al., 2009¹⁴). And many of the areas which are expected to experience the greatest climate change impacts coincide with regions that are expected to see some of the highest traffic growth. This is relevant to adaptation and resilience in two ways. Firstly, when an airport is operating at or close to capacity the time it takes to recover from a perturbation such as a disruptive weather event is much longer therefore any potential increase in weather-related disruption is likely to be further exacerbated (EUROCONTROL, 2013b). Secondly, building climate change resilience whilst managing a significant increase in traffic is a double challenge. Therefore these two issues should not be tackled in isolation but addressed in parallel. In particular, it is important to note that developing resilience to climate change as part of on-going operational and infrastructure improvements can be the most efficient and cost-effective way to achieve this. Therefore if measures are being taken to develop an airport to accommodate a greater number of passengers and flights then climate resilience should be viewed as an integral part of this.

4. Risk assessment: where to start?

To protect critical infrastructure and ensure future service continuity for operations, it is necessary to adapt and develop resilience to the potential risks of climate change. The question of course is how and when to act? A risk assessment is an effective way to establish whether and to what extent adaptation actions may be required and some aviation sector organisations are now doing this to assess to what extent climate change may be a risk for them. Of course, carrying out a risk

assessment does not commit an organisation to taking further adaptation action. However, it will identify where an organisation may want to consider taking measures to improve the resilience of its infrastructure and/or operations. This section will not discuss the risk assessment process in detail. Rather the intention is to highlight some of the key factors to think about when first considering a risk assessment and attempting to secure the commitment of senior management (Fig. 2).

A first issue to consider is how will the climate actually change in the local area or, in the case of an airline, the areas where it operates? The specific risks that may need to be addressed can vary greatly according to the climate impacts that will be experienced in the region. This requires coordination with local MET offices to obtain forecasts at a sufficient level of granularity to inform decision-making.

A second key question is who in the organisation is responsible for adaptation, and who needs to be involved? Adaptation is often, wrongly, perceived as solely an environmental issue. This is most likely for two reasons: because the issue is usually first identified by environmental people, and because of the associations with climate change. However, in reality, although it can have some environmental impacts, it is predominantly an operational, safety, infrastructure, mobility and business risk. Therefore an organisation needs to make sure all relevant parties are involved.

It is also vital to consider which other aviation and non-aviation actors need to be involved. Organisations do not exist in isolation. For example, airports serve as a node for providing passengers to airlines therefore impacts at airports can influence airline operations. And, vice versa, impacts on airlines can influence airport operations, for example en route delay can impact airport scheduling and slot management, whilst late arrivals can have an impact for noise quotas and curfews (Redeborn and Lake, 2016). There may also be some key risks that are external to the aviation sector. For example, will ground transport access or utilities supplies be available in the event of disruption, and can they be maintained if there are longer-term changes such as sea-level rise or temperature increase?

The purpose of these initial questions is twofold: firstly to facilitate an organization with identifying whether it has sufficient reason to

warrant a full risk assessment and, secondly, to identify a need for organizational action so as to secure top management buy-in. When it comes to a more thorough risk assessment, organisations may already have risk assessment methodologies, and integrating climate adaptation into an overall risk management strategy rather than treating it in isolation may well be the most efficient and effective. Alternatively, organizations could use or adapt an existing climate risk assessment methodology developed for climate change impact assessment by another aviation organization such as those developed by London Heathrow airport, The French Directorate General of Civil Aviation or Avinor, the Norwegian Air Navigation Service Provider and Airport operator (DGAC/STAC, 2013; Larsen, 2015; LHR, 2011).

5. Building resilience

Once a risk assessment has been carried out, an organisation needs to decide how and to what extent it wants to take action and then develop a climate adaptation strategy and plan. This section will both consider the decision-making process and identify potential measures to adapt and build resilience to some of the impacts identified in Section 2.

5.1. Planning for adaptation

This section will look at some key factors to consider when planning for adaptation. It should be noted that it is non-exhaustive and eventual decisions will be highly dependent on local circumstances and business models.

The overall challenge is how and when to act. Particularly for infrastructure, there are two main risks: over and under adaptation (Birkmann, 2016). A balance needs to be struck between the two and, whilst pre-emptive action is widely judged to be beneficial and cost-effective, reducing both costs and damages in the longer term, it should be based on the best available information to avoid excessive or inappropriate adaptation (ICAO, forthcoming). This is why a good risk assessment is essential: it would be prohibitively expensive, if not impossible, to achieve 100% resilience to climate change. Therefore, decisions will need to be made as to what level of resilience to achieve. Lower levels of adaptation may be cheaper but provide less resilience and for a shorter potential lifetime, whilst more robust adaptation may

provide greater resilience but at a higher cost (Eisenack, 2016).

Eventual decisions will need to weigh up both the criticality of the elements and areas where adaptation action is required, e.g. what is the impact if an element is unavailable or damaged, and the actual human and financial resources which are available (Birkmann, 2016). Moreover, as climate may change differently or more quickly than projected, or adaptation measures may need to be reinforced or altered, plans should ideally be flexible and reviewed at regular intervals (Eisenack, 2016; ICAO, in press). Bad decisions can incur substantial costs, both financially and in terms of damage and service continuity. Therefore, don't confuse decisiveness with good decisions by acting in haste.

One set of measures which are widely considered to be cost-effective are “low-regrets”, “no-regrets” and “win-win” measures. These are measures that are intended to address another issue such as capacity, but which also help to build resilience. Other cost-effective actions include so-called “soft” measures such as training, sharing of best practices and peer-to-peer support. And, finally, continuing and increasing communication and collaboration at local, regional and global level, and across sectors, will be required. This will be further explored in section 5.3 (cross-sector collaboration) and section 6 (Priority 4: communicate and elaborate).

5.2. Potential resilience measures by impact

This section will identify some of the potential resilience measures available to address each of the impacts identified in section 3. It should be noted that it is intended to give an indication only and is not an exhaustive list. Resources such as the Airport Cooperative Research Programme Climate Change Risk Assessment Guidance (ACRP, 2014) can provide further information on identifying specific resilience measures.

5.2.1. Changes in precipitation

Current aerodrome surface drainage capacity may be insufficient to deal with more frequent and intense precipitation events, leading to increased risk of runway and taxiway flooding from individual precipitation events or from rising water tables due to increased ground saturation. It may be possible to assess the risk by calculating the current surface drainage capacity against future precipitation forecasts.

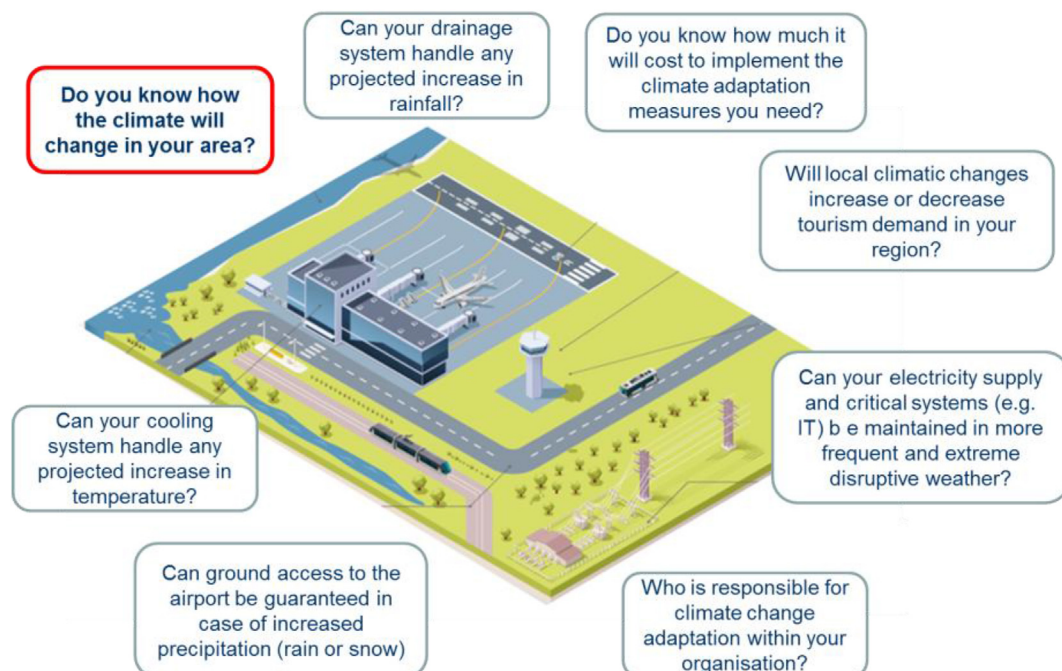


Fig. 2. Climate change risk assessment: a starting point. (Based on EUROCONTROL et al., 2014)

Adaptation and resilience measures include increasing surface drainage capacity or relocating electrical infrastructure (EUROCONTROL, 2013b; ICAO, *in press*). At Ottawa International airport in Canada runways have been grooved to improve traction and drainage during heavy precipitation events and this is understood to be being implemented at several other US and Canadian airports (Schwanz, 2014). Consideration should also be given to ensuring the continuity of ground transport access (EUROCONTROL, 2013b).

For areas where a decrease in precipitation drought and reduced water availability may be a challenge to airport operations, measures to reduce water consumption, or increase supply, will need to be considered such as reusing water or harvesting rainwater. Dallas Fort Worth airport is working several to reduce its water consumption through use of reclaimed water. This is a “win-win” benefit which also reduces costs and increases drought resistance (ACRP, 2012).

5.2.2. Increased convective weather

For areas at risk of increased severity in storms, possible adaptation measures may include reinforcing infrastructure so that it can withstand stronger winds (ICAO, *in press*). From an operational perspective, strategies and processes such as Airport Collaborative Decision Making (A-CDM) can be put in place to proactively manage demand when a severe weather event is considered highly probable. A-CDM has been fully implemented at 22 European airports to support the optimisation or airport operations. (EUROCONTROL, 2013a,b). The meso-scale convective systems identified in section 3.2 have the potential to impact multiple hub airports in a region. This may reduce the choice of diversionary airports whilst those that are available may not have sufficient capacity for the traffic which they need to accommodate. Consequently, dynamic capacity-based flight planning may be required (Burbidge, 2016).

5.2.3. Changes in temperature

In locations where significant temperature increases are expected runways and taxiways may need to be resurfaced with materials that can withstand higher temperatures. In areas where higher temperatures may be a challenge for aircraft take-offs, moving heavier long-haul traffic to earlier or later in the day could be considered, although this has impacts for scheduling and noise impact at both the departure and airport. The potential for increased cooling requirements should be accounted for in airport design, planning and retro-fitting. Long-term traffic demand analyses should be considered as part of medium to longer term business planning or as part of the business case for new infrastructure (Burbidge, 2014; ICAO, *in press*).

5.2.4. Changes in wind patterns

For an airport this is a challenging risk to adapt to. Where an airport has a crosswind runway, operations can be adapted to changing wind conditions. More drastically, an airport could include making changes to the current runway position/orientation and length to accommodate aircraft that are unable to operate in stronger crosswinds conditions, or adding a crosswind runway in order for aircraft that cannot operate in strong crosswinds to be able to do so (ICAO, *in press*). En-route, trajectories may need to be changed to optimise (eastbound) and reduce (westbound) the impacts of a stronger jet stream (Williams, 2016).

5.2.5. Sea-level rise and storm surges

Depending on location, economic factors, and operational needs, resilience measures may include building infrastructure higher or reinforcing existing infrastructure, building or improving sea defences, retaining or introducing natural barriers, allowing a certain degree of inundation as long as safety is not compromised, and being prepared to replace, repair or relocate assets as needed (ICAO, *Forthcoming*; EUROCONTROL, 2013b). Introducing or tightening standards for infrastructure could also be considered. For example, the Norwegian Airport operator and ANSP, Avinor, has introduced guidance stipulating that

runways should not be built lower than 7 metres above sea level whilst all exposed runways at coastal airports have undergone an extensive programme to increase wave and storm surge protection (Larsen, 2015). At Oakland airport in California, sea level rise has been incorporated into design requirements for the perimeter dike as part of broader planning for risk reduction. The dike was raised by 1 foot and will also be able to handle additional load. Although it was noted that sea level models do not provide conclusive information on projected sea level rise so averages of modelling results were used to calculate requirements (ACRP, 2012).

5.2.6. Desertification

Potential adaptation measures include designing “windbreaks” to reduce dust and sand, planting trees that require little water, and using recycled water where ever possible (ICAO, *in press*).

5.2.7. Biodiversity

Monitoring of changes in local wildlife and migratory patterns is recommended (ICAO, *forthcoming*). Adaptation measures will need to be tapered to specific local circumstances but may include modifying local habitat to discourage wildlife from encroaching on the airport, measures to scare wildlife away or modifying flight paths in the event of large flocks of migratory birds.

5.3. Cascading effects

Finally, as touched upon in section 4, links and dependencies with other actors should not be underestimated. It is important to think about “cascading effects” e.g. if one element in the system or actor is impacted how does that impact the rest of the system or other actors, both in-sector and between sectors. For example, if there is an impact on the energy sector and energy supply is interrupted then this has implications for the operation of the airport unless it has an adequate alternative power source. Loss of power supply may also have an impact on water supply which can have an additional rebound effect on the operation of the airport. Therefore it is important to identify potential interdependencies and measures to reduce impacts. A mapping of which elements and actors can impact each other and associated measures to address this is useful. However, particularly when it comes to rebound effects this is a complex issue, not least because different components of the same system can be susceptible to different vulnerabilities and so may need individual assessments (Groth, 2016).

6. Key priorities for action

In 2013 EUROCONTROL carried out a consultation with European aviation stakeholders to determine to what extent they considered climate change to be a risk to their organisations and whether they were beginning to take adaptation action. The results are discussed in Burbidge (2014). As part of the consultation an online survey for operational stakeholders was carried out. 35 valid responses were received, predominantly from airports and air navigation service providers (ANSPs), covering the main European climate zones. The survey results demonstrated that although a limited number of organisations had begun to take action to address the risks of climate change many others were not yet considering the potential risk. The key reasons cited for this were lack of information and guidance, and lack of awareness of the risk itself. This indicated that, at that point in time, this was still an emerging issue where organisations felt that they don't have a lot of information or guidance material to help them address this risk.

As a result, in 2014 Eurocontrol worked in collaboration with a group of seven air transport organisations¹ to develop some awareness

¹ ACI-EUROPE, AENA, Avinor, DGAC/STAC, London Heathrow, Manchester Metropolitan University, NATS. www.eurocontrol.int/resilience.



Fig. 3. Four key priorities for adapting global aviation to a changing climate.

material in this area. The outcome was a factsheet providing: an overview of some of the key climate risks for aviation; a checklist of questions for beginning to assess whether climate change is a risk for an organisation; a set of case studies from organisations who are already taking action to adapt to climate change; and a resource list of sources for further information on both risks and impacts and more detailed advice on how to carry out a risk assessment.

Following the positive response to the factsheet, EUROCONTROL worked with Manchester Metropolitan University to organise a workshop to try to identify the key priorities for action to adapt European aviation to a changing climate. The workshop had 30 participants, including industry stakeholders (representatives from airlines, airports, ANSPs and manufacturers), academia (academics and researchers from universities and research institutions in the UK, Germany, Greece and Italy) and European policy makers.

The morning session presentations consisted of a series of presentations on existing work and thinking on the topic of aviation adapting to climate changes. The purpose of the afternoon session was to identify the priorities for future action in order to address the gaps and weaknesses that the group believe exist. The session was conducted in break-out groups with participants split into five groups of six people. The membership of each group was predefined to ensure that the groups had a mix of expertise and organisational types and each group had a pre-appointed facilitator. Each group was asked to:

1. Reflect on the presentations from the morning and identify any key messages. Discuss priorities going forward.
2. Identify and reach consensus (if possible) on three key priorities for future action for making aviation climate resilient e.g. research, best practice, communication/collaboration and capacity building.
3. Provide a summary of discussions including additional priorities identified that were not listed in the top three (see 2. above).

Following the discussion, each group presented their top three priorities to the workshop. The priorities were discussed and ideas were grouped according to theme. Following the workshop, the workshop chairs produced a full list of the priorities identified, grouped according to “priority area,” and circulated it to participants for final agreement. This resulted in a set of four consensus key priorities for action (Fig. 3):

6.1. Priority 1: understanding the problem

There are two aspects to this priority. Firstly, it is necessary to review and frame the challenge from a holistic sectoral perspective. This entails identifying the key potential impacts for each stakeholder and the network as a whole. Following this it can be identified what knowledge of those impacts already exists and where are the knowledge gaps so that research priorities can then be identified.

6.2. Priority 2: assessing the problem

This addresses risk assessment. A key factor to consider here is the development of a generic impact matrix from a common baseline e.g. a 3 °C temperature rise and Xm of sea-level rise. Although this would be extremely challenging to achieve, it is recognized that it is essential to ensure that adaptation actions are coordinated and effective. Ideally, comparable risk assessment methodologies should also be used to facilitate the development of compatible local and network measures.

6.3. Priority 3: actions to adapt

This entails both identifying operational and infrastructure measures to build resilience to both increased disruption and changing baseline conditions. See Section 5.2 for some examples. It also involves identifying win-wins and no-regrets measures such as those identified in section 5 and trade-offs especially where environmental improvements may introduce vulnerabilities, for example reducing the weight of engines to make them more fuel efficient may make them more susceptible to damage from icing.

6.4. Priority 4: communicate and collaborate

Ongoing communication and collaboration, both within Europe and at global level was identified as key. This may, inter alia, involve: establishing a core group or forum on adaption within Europe so as to maintain momentum and open the door to greater participation; collaboration in research and information sharing; the combination and coordination of knowledge and research from other regions and sectors, and; communication: awareness-raising and assessment/dissemination of best practice both within Europe and globally.

Taking a global and regional perspective warrants particular emphasis: as has been seen with recent high-profile disruptive events, if there is a perturbation in one part of the network that can have a knock-on effect for the network as a whole. Therefore it is important not to act in isolation but to also look at this from a more holistic network perspective: if there is a vulnerability in one part of the network, that can reduce the resilience of the overall network. Consequently it is important to identify impacts and implement resilience measures across the globe.

7. Conclusions

The purpose of this paper was to further clarify the risks which the aviation sector is likely to face from climate change and how to begin assessing and addressing those risks. It found that a key step is carrying out a risk assessment to determine the nature and extent of the impacts which an organisation may need to address. This assessment can then be used to inform the development of a climate adaptation strategy and plan. Adaption actions to address most key risks can be identified, though some, such as building resilience to cross-winds at an airport, may be more challenging to address, whilst low-regrets actions and softer measures such as training can be efficient and cost-effective. The overall challenge is how and when to act. A balance needs to be struck between over and under adaptation and, whilst preemptive action is widely judged to be beneficial, it should be based on the best available information to avoid excessive or inappropriate adaptation.

The paper also discussed a stakeholder workshop run by Manchester Metropolitan University and EUROCONTROL. The workshop identified four priority action areas for the sector, namely: better understanding the problem by further clarifying potential impacts, existing knowledge and research priorities; assessing the problem, ideally with compatible risk assessment methodologies and working from the same baseline; initiating actions to adapt both operations and infrastructure, including the identification of no-regrets measures and trade-offs, and; continuing and increasing communication and collaboration, both within Europe

and at a global level.

The aviation sector is making progress to address climate change risk. A reasonable qualitative understanding of both the potential impacts and the high-level actions which are needed to address them has been developed. But uncertainties remain and, to date, little progress has been made in *quantifying* what climate change implies from an operational perspective. Moreover, as a vulnerability in one part of the global aviation network can impact the network as a whole, risks not only need to be identified and addressed at the level of individual organizations, but rather the global sector needs to work together to learn from each, collaborate and communicate, and build partnerships for action.

References

- Airport Cooperative Research Programme Synthesis (ACRP), 2012. ACRP 33: Airport Climate Adaptation and Resilience. Transportation Research Board of the National Academies, Washington.
- Airport Cooperative Research Programme Synthesis (ACRP), 2014. ACRP 147: Climate Change Adaptation Planning: Risk Assessment for Airports. Transportation Research Board of the National Academies, Washington.
- Birkmann, J., 2016. The impacts of global and regional change on the resilience of critical infrastructures. In: Adaptation Future Conference 2016, Rotterdam, the Netherlands.
- Burbidge, R., 2014. Aviation Climate Resilience: clarifying the impacts and identifying the barriers. In: 18th Air Transport Research Society World Conference, Bordeaux, France.
- Burbidge, R., 2016. Adapting European airports to a changing climate. *Transport. Res. Procedia* 14, 14–23.
- DGAC/STAC, 2013. Vulnérabilité des aéroports au face de changement climatique, Service Technique de l'aviation Civile. Directorate Général d'Aviation Civile, Paris.
- European Environment Agency, (EEA), 2012. Climate Change Impacts and Vulnerability in Europe 2012. European Environment Agency, Copenhagen.
- Eisenack, K., 2016. Adapting long-lived infrastructure to uncertain climate change. In: Adaptation Future Conference 2016, Rotterdam, the Netherlands.
- EUROCONTROL, 2013a. Long-term Forecast Flight Movements 2009 – 2030. STATFOR, EUROCONTROL, Brussels.
- EUROCONTROL, 2013b. Challenges of Growth 2013: Climate Change Risk and Resilience. STATFOR, EUROCONTROL, Brussels.
- EUROCONTROL, ACI-EUROPE, AENA, Avinor, DGAC, Heathrow, NATS, Manchester Metropolitan University, 2014. Adapting Aviation to a Changing Climate Factsheet. EUROCONTROL, Brussels.
- Groth, M., 2016. The relevance of cascading effects for adapting critical infrastructure to climate change. In: Adaptation Future Conference 2016, Rotterdam, the Netherlands.
- ICAO, (in press). Airport Planning Manual Part II, second ed. International Civil Aviation Organisation, Montreal.
- Larsen, O.L., 2015. Climate change is here to stay. What about the airport infrastructure? *J. Airt. Manag.* 9, 264–269.
- Levina, E., Tirpak, D., 2006. Adaptation to Climate Change: Key Terms. Organisation for Economic Cooperation and Development, Paris.
- Heathrow Airport (LHR), 2011. Climate Change Adaptation Reporting Power Report. Heathrow Airport Limited, London.
- Mach, K.J., Planton, S., von Stechow, C., 2014. Annex ii glossary. In: Pachauri, R.K., Meyer, L.A. (Eds.), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, pp. 117–130.
- McCarthy, R., Budd, L., 2010. Case-study 3: potential changes in severe convection in maastricht upper area airspace. In: Thomas, C., Drew, A.J. (Eds.), *Challenges of Growth Environmental Update Study: Climate Adaptation Case Studies*. EUROCONTROL, Brussels, pp. 93–120.
- Morse, A., Prentice, C., Carter, T., 2009. Assessment of climate change impacts. In: van der Linden, P., Mitchell, J.F.B. (Eds.), *ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project*. Met Office Hadley Centre, Exeter, pp. 107–129.
- Redeborn, B., Lake, G., 2016. Gatwick Independent Arrivals Review: Report and Recommendations, Gatwick Airport.
- Schwanz, M., 2014. Ottawa Int'l Sets Precedent with Grooved Runway, Airport Improvement. <http://www.airportimprovement.com/article/ottawa-intl-sets-precedent-grooved-runway>, Accessed date: 1 February 2018.
- Thomas, C., McCarthy, R., Lewis, K., Boucher, O., Hayward, J., Owen, B., Liggins, F., 2009. Challenges to Growth Environmental Update Study. EUROCONTROL, Brussels.
- Williams, P.D., 2016. Transatlantic flight times and climate change. *Environ. Res. Lett.* 11 (2).
- Williams, P.D., Joshi, M.M., 2013. Intensification of winter transatlantic aviation turbulence in response to climate change. *Nat. Clim. Change* 3, 644–648.